Shear zones in dry granular materials

Ph.D. Thesis Booklet

Balázs Szabó

Institute for Solid State Physics and Optics
Wigner Research Centre for Physics
Hungarian Academy of Sciences

Supervisor: Tamás Börzsönyi, Ph.D.

Eötvös Loránd University
Graduate School of Physics
Head of the School: Prof. Dr. László Palla, D.Sc.

Materials Science and Solid State Physics Program
Program Leader: Prof. Dr. János Lendvai, D.Sc.

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Introduction

Granular materials can be found everywhere around us and it covers the Earth due to various natural processes. Their dynamics is driven by well-known forces like hard core repulsion, friction or gravity. However, because of the large number of interacting bodies, numerous phenomena are observed that are special to granular materials. In the following I will introduce the most relevant papers connecting to my dissertation, the most important experimental details, and collect the main conclusions.

Objectives

In this dissertation I will focus on one phenomenon: applying shear on a granular sample often (but not necessarily) leads to definite regions where the shear is localized, depending on the geometry of the setup[1]. In many cases this sheared region (called shear zone) is located close to a container wall. The properties of such shear zones were studied in a relatively large number of previous papers. The sheared region is always a small number of particle diameters wide in these cases. But if shear is forced to develop in the bulk of the sample by applying an appropriate geometry, its width can be much larger. For example if the bottom wall of the shear cell is divided into two parts, and shear is applied by moving these two parts with respect to each other, the sheared region can develop far from the surrounding walls. The former types of shear zones are referred as narrow shear zones while the latter ones are called wide shear zones[2].

For wide shear zones the zone width in the stationary state can be tuned by the filling height of the material. The surface zone width was found to increase with increasing filling height according to a power law with an exponent between 0.5 and 1 in experiments[3], and around 2/3 in numerical studies[4]. One can find a few experimental results in the literature about the shape of the zone in the bulk of the sample, however, the data were not fitted by any function due to the low resolution of the exported data. The simulations by Ries et al.[4] suggested that the width of the sheared region as a function of the local height can be well fitted by a quarter of a circle, if the local height is normalized by the filling height and the zone width is normalized by the surface zone width. We aimed to explore

[1] GDR MiDi, *Eur. Phys. J. E.* vol. 14, pp. 341-365, 2004.
[2] Fenistein and van Hecke, *Nature* vol. 425, p. 256, 2003.
[3] Fenistein et al., *Phys. Rev. Lett.* vol. 92, p. 094301, 2004.
[4] Ries et al., *Phys. Rev. E* vol. 76, p. 051301, 2007.

the shape of the shear zone for the whole cross section of the sample with a high accuracy to test this claim [P1].

The evolution of the shear zone width was investigated predominantly for narrow shear zones. Three types of time dependent effects were studied: the transient from an initially random distribution of the particles, when the direction of shear is reversed or during an oscillatory shear. For wide shear zones, the numerical simulations by Ries et al.[4] found that for a random initial configuration of the sample the zone width is wider at the beginning of the shear than in the stationary state. They introduced a possible explanation, which says that at the beginning of the process it is easier to shear the material. When the sample is deformed, a higher resistance to shear is reached in the center region, while the outer parts still have a smaller resistance. In that stage of the process the shear zone is wider compared to the stationary state. As the region with the higher resistance to shear grows during the process, the zone width continuously decreases to its final value. We aimed to accurately map the evolution of the zone width for two initial configurations: a random configuration or for reversed shear. The influence of the particle shape is also an open question, therefore we repeated the measurements with spherical, irregular and elongated particles [P1].

Elongated or flattened particles can easily align due to shear flow in nature for very different particle sizes. The static properties of granular materials consisting of non-spherical particles were studied in numerous papers. However, the dynamics of such systems are far from understood. The reason why non-spherical particles have a more complex behavior is that in contrast to spheres, for elongated particles the contact point in general is not located on the line between the two centers of mass, and also the tangent plane of the contact is not perpendicular to that line. The book by Ehrentraut and Chrzanowska[5] includes an orientation distribution of elongated rice grains detected in an inclined plane flow. They revealed that the particles in average are not parallel to the flow field. We aimed to investigate the alignment of elongated grains in split-bottom shear cells [P2, P3, P5]. Both the stationary state and the initial transient effects were examined to explore the orientation of macroscopic elongated grains. A good review paper collecting the results about elongated granular materials including our results is written by Börzsönyi and Stannarius[6].

[5] Ehrentraut and Chrzanowska, *Dynamic Response of Granular and Porous Materials under Large and Catastrophic Deformations* vol. 11 of Lecture Notes in Applied and Computational Mechanics, pp. 343-364, Springer Berlin Heidelberg, 2003.

[6] Börzsönyi and Stannarius, *Soft Matter* vol. 9, p. 7401, 2013.

The rotation of a single ellipsoid in a sheared Newtonian fluid was calculated analytically by Jeffery[7] in 1922. He found that the angular velocity depends on the actual orientation of the ellipsoid: when the major axis of the particle is parallel to the shear flow, it rotates slower; but when these two directions are perpendicular to each other, the particle rotates faster. For more elongated ellipsoids the difference in the angular velocities is larger. We extracted the rotation of elongated granular particles and compared our results to the work of Jeffery [P3, P5]. Another field of physics, where the ordering of elongated objects were studied intensively in the last 50 years is nematic liquid crystals. We briefly described the similarities and differences between granular materials and liquid crystals [P2, P5].

In geological systems we can typically find different granular materials layered on each other due to different natural processes separated in time. Shearing of such systems can be observed when e.g. geological faults, landslides, rock avalanches occur. However, previous granular studies focused mainly on homogeneous samples, and only a few papers discussed the shear of layered granular samples. One of these works is based on a variational model introduced in the paper by Unger et al.[8] and its numerical extension, the „fluctuating narrow band model"[9], which successfully described not only the position, but also the width of the shear zone quantitatively for homogeneous samples. Both models are based on a cross section of the shear cell. Increasing an external shear force, the material will yield along the path which corresponds to the minimal friction. The frictional force for a specific path is given by the integral of the effective friction coefficient along the path.

Unger found an interesting result provided by this variational model and validated by discrete element method simulations[10]. If the two ends of the shear zone are located in materials with different effective friction coefficient, the shear zone will change its direction at the layer boundary between the two materials according to the granular version of Snell's law. According to Snell's law for a two component optical system, the light beam changes its direction at the boundary of the two materials in a way that the ratio of the sine of the angles of incidence equals to the ratio of the optical densities of the two materials. In our granular systems a very similar law is valid, but the optical densities are replaced by the effective friction coefficients. In addition to the discrete element method simulations by Unger[8], two papers were addressed to test this result experimentally in

[7] Jeffery, *Proc. Roy. Soc. London A* vol. 102, p. 161, 1922.
[8] Unger et al., *Phys. Rev. Lett.* vol. 92, p. 214301, 2004.
[9] Török et al., *Phys. Rev. E* vol. 75, p. 011305, 2007.
[10] Unger, *Phys. Rev. Lett.* vol. 98, p. 018301, 2007.

different geometries. Knudsen and Bergli[11] used a geometry similar to the original paper, while Börzsönyi et al.[12] applied a somewhat different setup[13]. We aimed to study further configurations, detect the complex shape of shear zones and compare the results with geometric optics to reveal the limit of this analogy [P4, P6].

Methods

Shear flow was studied in two different experimental configurations, both are widely used in previous works. In the straight split-bottom shear cell the container consisted of two L shaped sliders and they were moved with respect to each other to generate a shear flow. In the cylindrical split-bottom shear cell a circular plate was rotated at the bottom of the container while the outer ring was at rest. Although a slightly different analyzing method was applied, we expected that the zone width behaves similarly for the two geometries. Using both types of setups has the possibility of testing the effect of the curved streamlines in the cylindrical shear cell.

Data collection was realized with optical cameras and three dimensional imaging techniques, namely with nuclear Magnetic Resonance Imaging (MRI) and X-ray Computed Tomography (CT). Optical devices provided a large amount of images about the surface of the sample with a high resolution, while MRI and CT gave important information about the bulk of the sample. Applying different data acquisition methods had the advantage of providing complementary results and it also enabled some cross-check.

The collected two and three dimensional images were analyzed by specific Particle Image Velocimetry (PIV) and Particle Tracking Velocimetry (PT) software. The PIV data allowed us to calculate the local strain of the sample, while PT data was used to determine the orientation and rotation of elongated particles in shear flows. A substantial part of my work was to develop a PT code to detect the orientation of tracer particles on the collected two dimensional images.

[11] Knudsen and Bergli, *Phys. Rev. Lett.* vol. 103, p. 108301, 2009.
[12] Börzsönyi et al., *Phys. Rev. E* vol. 80, p. 060302(R), 2009.
[13] This work formed the basis of my Diploma thesis.

Theses

1. For sheared granular samples I determined experimentally the evolution of the width of the shear zones formed in split-bottom shear cells by using optical imaging. The width of the sheared region as a function of the local strain was found to have a non-monotonic shape including a strongly decreasing part for two different initial conditions (random and oppositely sheared). The local strain, at which the sharp zone width decrease happens, was found to be larger for elongated grains than for spherical particles, while the ratio between the initial and the stationary zone width increased with the shape anisotropy of the grains [P1].

2. Using X-ray Computed Tomography I characterized the packing density of the grains, the orientational ordering as well as the width of the shear zone simultaneously as a function of the local strain for an initially random configuration using both elongated and spherical granular materials. The characteristic strain rates describing Reynolds dilation and the evolution of the average alignment did not depend on the shape of the particles, but strain scales corresponding to the narrowing of the shear zone and the evolution of the orientational order parameter systematically increased with the particle elongation [P1].

3. I have developed a particle tracking software which detected the orientation and position of granular particles consisting of elongated grains in shear flows recorded by optical imaging. Under stationary shear the average grain alignment was found to be not parallel to the streamlines, but it was slightly tilted towards the velocity gradient. The alignment angle was measured to be independent of the shear rate across three decades. The shear induced orientational order increased and the alignment angle systematically decreased with increasing grain aspect ratio. Comparing nearly ellipsoidal and cylindrical particles with the same aspect ratio, the cylindrical grains had a smaller average alignment angle. The alignment of elongated particles was found to be very similar at the surface and inside the material determined by X-ray Computed Tomography measurements [P2, P3, P5].

4. I determined the evolution of the alignment of granular particles in shear flows started from a random orientation distribution or from an oppositely sheared configuration by analyzing optical measurements. In the case of the initially random distribution, the average alignment angle was found to decrease to its stationary value, and the order parameter was measured to increase monotonically until it reached its final value. For the case of reversed shear, the average alignment angle increased, i.e. the grains reached the new preferred direction by rotating backwards, and the order parameter decreased at the beginning of the transient before increasing back to the stationary state, as the original ordering got destroyed first. The angular velocity of individual grains was also determined. This depends on the local configuration and the interactions with the neighbors, thus involves large statistical noise. The average rotation speed of many grains was found to depend systematically on the grain orientation. Namely, particles parallel to the flow are in average rotating slower than those perpendicular to the flow direction. Grains under stationary shear rotate typically in the direction dictated by the flow, however, during the initial transients, particles which are close to parallel to the streamlines in average rotate backwards [P2, P3, P5].

5. I determined experimentally the complex shape of the shear zones for layered granular systems consisting of two kinds of particles with different effective friction coefficients by applying the excavation method and analyzing Magnetic Resonance Imaging measurements. When one end of the shear zone was forced to be in the high friction part of the sample, the shear zone was found to leave the high friction part, it changed its direction at the vertical layer boundary and it propagated parallel to the layer boundary lying entirely in the low friction part of the sample. In a different geometry, where both ends of the shear zone were forced to be in the high friction part of the sample, the shear zone left the high friction part, it went parallel to the layer boundary between the two materials, and then it returned to the high friction layer. Both observations were found to appear only if the low friction part is close enough to the fixed ends of the shear zone. The position of the layer boundary was calculated, which corresponds to the transition between the cases when the zone crosses the boundary and when it does not cross [P4].

Conclusions

The main objective of this dissertation is to answer a couple of open questions of sheared granular materials listed in the Objectives section. In the following I will summarize the consequences of our results.

We successfully measured the stationary width of the shear zone for the whole cross section in the straight shear cell by using MRI technique [P1]. The stationary shape of the zone width could be well fitted by a quarter of a circle as suggested by Ries et al.[4]. The evolution of the zone width was detected optically for two initial conditions: for an initially random configuration or when the direction of shear is reversed. Spherical, irregular as well as elongated particles were investigated. The width of the sheared region was characterized as a function of the local strain γ. For the initially random configuration the shear the zone was wide at the beginning, then the width decreased rapidly between around $0.1 < \gamma < 1$, but for large strain it slightly increased back before reaching the stationary value. The rapid decrease occurred at a larger strain for particles with larger shape-anisotropy. For the case of reversed shear, at the beginning of the process the zone was found to be wider than any time during the random transient. The reason for this is that during the shear small empty volumes behind the particles develop, and after reversing the shear direction the grains can easily move into these small volumes, which leads to a wider shear zone. In this case the zone width immediately started to decrease. At around $\gamma \approx 0.1$ the quick narrowing stopped and the width started to increase back until $\gamma \approx 1$. Above $\gamma \approx 1$ the zone width curves became very similar to the ones measured during the random transient, meaning that after the grains pass their neighbors, the system forgets its original state.

The stationary alignment of elongated grains under shear was measured by optical and CT devices for two types of particle shapes: rice grains as well as cylindrical glass rods and wooden pegs, all with a couple of different aspect ratio values [P2, P3, P5]. For all the investigated materials the particles had a preferred direction close to parallel to the streamlines, but in average they were tilted towards the velocity gradient by an angle called average alignment angle Θ_{av}. The orientational ordering was captured by the order parameter S. Both quantities were found to be nearly independent of the shear rate across three decades. The value of Θ_{av} decreased with increasing aspect ratio, and for rice grains we detected a systematically larger Θ_{av} than for cylindrical particles with the same aspect ratio. For grains with larger elongation and smaller Θ_{av} the order parameter was larger. This alignment process is very similar to nematic liquid crystals despite the totally different forces in the two systems. For liquid crystals the average alignment of the molecules - described with the director - does not change with the shear rate, and for a larger order parameter Θ_{av} also becomes smaller. These similarities between the two distinct fields of physics indicate that the shear induced alignment has a strong geometric origin.

The evolution of the orientational ordering was followed optically for one type of particles with cylindrical shape [P2, P3]. Two types of initial configurations were prepared similarly to the zone width measurements: a random configuration or when the sample was previously sheared in the opposite direction. For the random initial configuration Θ_{av} smoothly decreased to its final value because the flow field rotates the particles in this direction. At the same time S continuously increased to its stationary value. The evolution of S was much faster than that of Θ_{av}. For the case of reversed shear, we found that the particles preferred to reach the new Θ_{av} by rotating with a positive angular velocity, which is the opposite direction of what the flow field dictates. The orientational order parameter first decreased as the original ordering was destroyed, and later it increased back to its initial value as the new ordering developed. Interestingly, the average angular velocity of the particles in the stationary state was found to be very similar to the Jeffery solution discussed in the Objectives section, as the ratio of the angular velocities for misaligned and nearly aligned orientations increased with increasing aspect ratio. During both transients, particles which were nearly parallel to the flow direction rotated backwards in average.

In order to connect the evolution of the ordering to other physical processes, we investigated CT measurements and calculated the zone width, the average alignment angle, the orientational order parameter and the packing density for an initially random distribution of the particles [P1]. Both Θ_{av} and S had an evolution similar to the optical measurements. The evolution of the zone width had a much better resolution in the optical measurements, and only the most significant decreasing part was captured with the CT device. As for the packing density, the absolute values detected here should not be compared to other values in the literature, as it depends slightly on the binarization threshold used to analyze the CT tomograms. The packing density for all materials decreased due to the Reynolds dilation. For elongated particles, it slightly increased back at large strains, which was attributed to the development of the orientational order. The Reynolds dilation and the decrease of Θ_{av} had a characteristic strain scale independent of the aspect ratio of the particles. For the narrowing of the shear zone and for the increase of S this strain scale increased with increasing aspect ratio, and their values were close to each other indicating that they might be connected.

The complex shape of shear zones in layered granular materials was measured in two experimental geometries (described later) by using two samples with different effective friction coefficients [P4, P6]. One way of detection was the excavation method, where we determined the displacement of the sample optically for the whole cross section by coloring half of the grains for each material, carefully removing the sample layer by layer after shear and detecting the distortion of the originally planar colored-uncolored border. Additional MRI scans were recorded for one of the geometries, and the result was very similar to the ones provided by the excavation technique. In one type of measurements the container consisted of two L shaped sliders, which were moved with respect to each other to generate a shear flow. In this case, the boundary between the two materials was a vertical plane. The shear zone started in the high friction layer. The zone was found to leave the high friction part of the sample, changed direction at the layer boundary and went to the surface vertically in the low friction part. This observation was similar to the limiting case of total reflection in optics. In the other type of measurements the bottom plate was moved to generate shear in the system, and the interface between the two materials was horizontal. The shear zone had both ends in the high friction part of the sample. We found that if the low friction layer is close enough, the zone is expulsed from the high friction layer, otherwise the zone is lying entirely in the high friction part. The angle of incidence on the high friction side of the layer boundary was found to be determined by the ratio of the effective friction coefficients. The critical distance between the end point or points of the shear zone and the layer boundary between the two materials was estimated for both geometries by assuming homogeneous or hydrostatic pressure through the sample. Our measurements were in good agreement with these calculations.

List of publications

Publications in peer reviewed scientific journals:

[P1] B. Szabó, J. Török, E. Somfai, S. Wegner, R. Stannarius, A. Böse, G. Rose, F. Angenstein, T. Börzsönyi, "Evolution of shear zones in granular materials", *Phys. Rev. E*, vol. 90, p. 032205, 2014

[P2] T. Börzsönyi, B. Szabó, G. Törös, S. Wegner, J. Török, E. Somfai, T. Bien, R. Stannarius, "Orientational Order and Alignment of Elongated Particles Induced by Shear", *Phys. Rev. Lett.*, vol. 108, p. 228302, 2012

[P3] T. Börzsönyi, B. Szabó, S. Wegner, K. Harth, J. Török, E. Somfai, T. Bien, R. Stannarius, "Shear-induced alignment and dynamics of elongated granular particles", *Phys. Rev. E*, vol. 86, p. 051304, 2012

[P4] T. Börzsönyi, T. Unger, B. Szabó, S. Wegner, F. Angenstein, R. Stannarius, "Reflection and exclusion of shear zones in inhomogeneous granular materials", *Soft Matter*, vol. 7, pp. 8330-8336, 2011

Publication in a peer reviewed conference proceedings:

[P5] R. Stannarius, S. Wegner, B. Szabó, T. Börzsönyi, "Shear alignment and orientational order of macroscopic rodlike grains", Powders and Grains 2013, 8-12 July 2013, Sydney, Australia, *AIP Conf. Proc.*, vol. 1542, p. 74, 2013

Publication in Hungarian:

[P6] B. Szabó, "Hogyan törik a szemcsés anyag? Avagy egy különös analógia az optikával", *Természet Világa*, vol. 143 (11), pp. 500-503, 2012

The publications below are not included in this dissertation:

- T. Börzsönyi, T. Unger, B. Szabó, "Shear zone refraction and deflection in layered granular materials", *Phys. Rev. E*, vol. 80, p. 060302(R), 2009

- S. Wegner, R. Stannarius, A. Boese, G. Rose, B. Szabó, E. Somfai, T. Börzsönyi, "Effects of grain shape on packing and dilatancy of sheared granular materials", *Soft Matter*, vol. 10, pp. 5157-5167, 2014